

THE HUMAN FACTORS OF WORKSTATION TELEPRESENCE

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ABSTRACT

Human-operated, remotely controlled robots (telerobots) are projected to play a pivotal role in the performance of assembly, maintenance, and servicing manipulation tasks, during construction and operation of the U.S. space station in the next decade. To reap the anticipated benefits of telerobotic systems---increased safety, efficiency, and productivity of task performance in space, accompanied by reduced costs---it is essential that the control requirements for telerobot operation are compliant with control capabilities and limitations of the human operator. The term workstation telepresence has been introduced to describe such human-telerobot compliance, which enables the human operator to effectively project his/her body image and behavioral skills to control of the telerobot itself. This report addresses major human-factors considerations for establishing high fidelity workstation telepresence during human-telerobot operation. Telerobot workstation telepresence is defined by the proficiency and skill with which the operator is able to control sensory feedback from direct interaction with the workstation itself, and from workstation-mediated interaction with the telerobot. Numerous conditions influencing such control have been identified. This raises the question as to what specific factors most critically influence the realization of high fidelity workstation telepresence? The thesis advanced in this report is that perturbations in sensory feedback represent a major source of variability in human performance during interactive telerobot operation. Perturbed sensory feedback research over the past three decades has established that spatial transformations or temporal delays in sensory feedback engender substantial decrements in interactive task performance, which training does not completely overcome. Similar, more recent laboratory studies with remote telerobot manipulators have confirmed in part the earlier findings. The goal of effective and safe interactive telerobot operation therefore may benefit from development of techniques which enable the interactive computer to detect, and compensate for, perturbations in sensory feedback before presentation of such feedback to the operator. A recently developed social cybernetic model of human-computer interaction can be used to guide this approach, based on computer-mediated tracking and control of sensory feedback. The report will conclude by indicating how the social cybernetic model can be employed for evaluating the various modes, patterns, and integrations of interpersonal, team, and human-computer interactions which play a central role in workstation telepresence.

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INTRODUCTION

Automation and robotics (A&R) will play a pivotal role in the development and operation of permanently-manned U.S. extraterrestrial outposts. One such outpost currently under development by NASA is Space Station Freedom, an orbiting space laboratory targeted for assembly in the mid-1990s. Projected A&R applications for the U.S. space station encompass over twenty major projects, including use of interactive teleoperated robots (telerobots) for assembly, servicing, and maintenance functions [1-3]. Telerobots are devices with mechanical arms for grasping and manipulation which are envisioned to play an integral role in space station operation. The devices are projected to have some of the same operational capabilities as an astronaut in a space suit. NASA and Bureau of Mines research also indicates that interactive A&R systems will be employed in mining lunar resources, in support of a lunar base in the 21st century [4-8]. Anticipated benefits of interactive A&R applications in space include a reduced crew size, increased crew productivity, consequent cost savings, and increased safety of the crew, concomitant with use of telerobots instead of crew members to conduct risky extravehicular (EVA) maneuvers [1,2]. For these benefits to be realized, it is essential that the human-factors design and operational characteristics of the human-computer/human-telerobot interface be compatible with the behavioral-physiological performance capabilities and limitations of the human operator. In the case of human operation of telerobots at remote sites (teleoperation), such compliance across the interface is described by the term telepresence, defined by NASA as "a teleoperation situation in which the operator has sufficient cues to simulate sensations that would be experienced in direct manual performance of the operations" [9].

This report provides a conceptual and technical analysis of the major human-factors issues which must be addressed in creating effective workstation telepresence during telerobot operation. A major focus of the analysis concerns the phenomenon of perturbed sensory feedback as a decisive influence on workstation telepresence. The term refers to the introduction of some sort of perturbation, or transformation, in the spatial, temporal, or physical properties of one or more modalities of sensory input to the human operator across the interface. Such perturbations alter the normal closed-loop control mechanisms of cognitive and motor perceptual behavior, and can thereby evoke substantial decrements in human performance during teleoperation.

The principle hypothesis advanced in this report is that perturbations in sensory feedback constitute a major obstacle to the creation of high fidelity workstation telepresence. As a result of

human-factors limitations of interface design, perturbations in sensory feedback arise routinely during human interaction with telerobotic systems. These limitations may be exacerbated by conditions prevailing in space environments. To address this problem, the following sections: (1) provide a human-factors analysis of telerobotic workstation telepresence; (2) outline the adverse effects of perturbed sensory feedback on interactive performance for behavior generally, and for telerobotic operation in particular; and (3) discuss how such effects can be managed operationally, based on use of a social cybernetic model of workstation telepresence to target research needs.

HUMAN-FACTORS ANALYSIS OF WORKSTATION TELEPRESENCE

During human performance with a telerobot via a teleoperation workstation, sensory feedback (visual, tactile, kinesthetic, and/or auditory) to the operator is generated by two sources: direct interaction with the workstation, and workstation-computer mediated interaction with the telerobot. To optimize workstation telepresence, the spatial, temporal, and physical properties of workstation and telerobot sensory feedback, as determined by the human-factors design of the teleoperation system, must be compliant with the sensory feedback control capabilities of the human operator.

This concept is illustrated in Figure 1, using the example of a movement-actuated (master-slave) telerobot manipulator. Effective control of the manipulator depends upon space, time, and force (kinesthetic) compliance between operational feedback from the telerobot slave sector, and motor behavioral control of this sensory feedback by the operator. If human-factors design problems cause spatiotemporal perturbations in sensory feedback, then compliance between sensory feedback and its control is compromised and performance suffers. Evidence from various sources suggests that because of human-factors design problems, both spatial and temporal perturbations in sensory feedback are a pervasive feature of interactive human-computer and telerobotic systems [10-14].

Figure 2 expands upon Figure 1 by schematically illustrating the major human-factors design issues that must be addressed in creating workstation telepresence [11]. Figure 2A shows a telerobotic manipulator under direct control, rather than computer-mediated remote control, by the operator. Integrated postural, transport, manipulative, and tremor movements are employed to control the spatiotemporal properties of manipulator operation, in relation to its master-control, actuator, and slave components (Figure 1). For the control task, the operator relies upon three major sources of sensory feedback: (1) reactive feedback from movements of body segment and limb effectors; (2) instrumental feedback from effector interaction with and movement of the manipulator master-control component; and (3) operational feedback from action of the manipulator slave component and its effect on the environment.

Figure 2B illustrates how these relationships are altered in the case of teleoperation of a remote manipulator. In this case, control of the manipulator is mediated through a master-control computer workstation, whose actual design for space

station telerobotic applications is still under development [15,16]. Direct reactive, instrumental, and operational sources of sensory feedback are generated by operator interaction with the workstation, rather than directly with the telerobot. Through display of video images from external cameras, plus tactile, force, and possibly auditory sensors mounted on or near the robot, the workstation provides indirect, computer-mediated reactive, instrumental, and operational sensory feedback information from activity of the telerobotic manipulator. Thus, during remote telerobot manipulation, the operator must simultaneously control sensory feedback from two major modes of interaction, namely direct interaction with the workstation plus workstation-mediated interaction with the telerobot manipulator. Collectively, this combination of direct plus indirect, computer-mediated feedback information may be referred to as telepresence sensory feedback.

Conclusions From Research on Cybernetic Anthropomorphic Machines

One of the first comprehensive conceptual and technical investigations of human-factors engineering requirements for effective workstation telepresence, as defined generally in Figures 1 and 2, was carried out during the fifties and sixties in the context of an extensive General Electric research and development program on cybernetic anthropomorphic (manlike) machines (CAMs) [11],

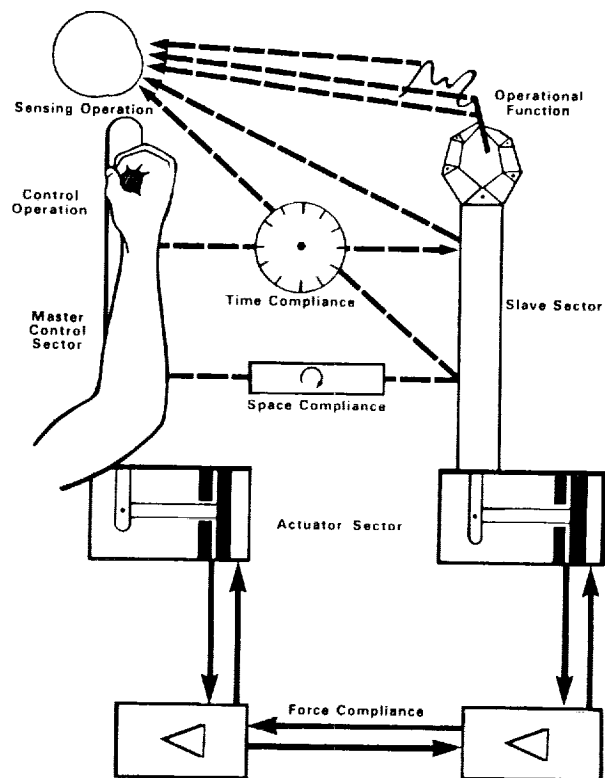


Figure 1. Human factors in control-display relationships in a manual manipulator. Normal spatial and temporal visual feedback compliance is essential for optimal performance.

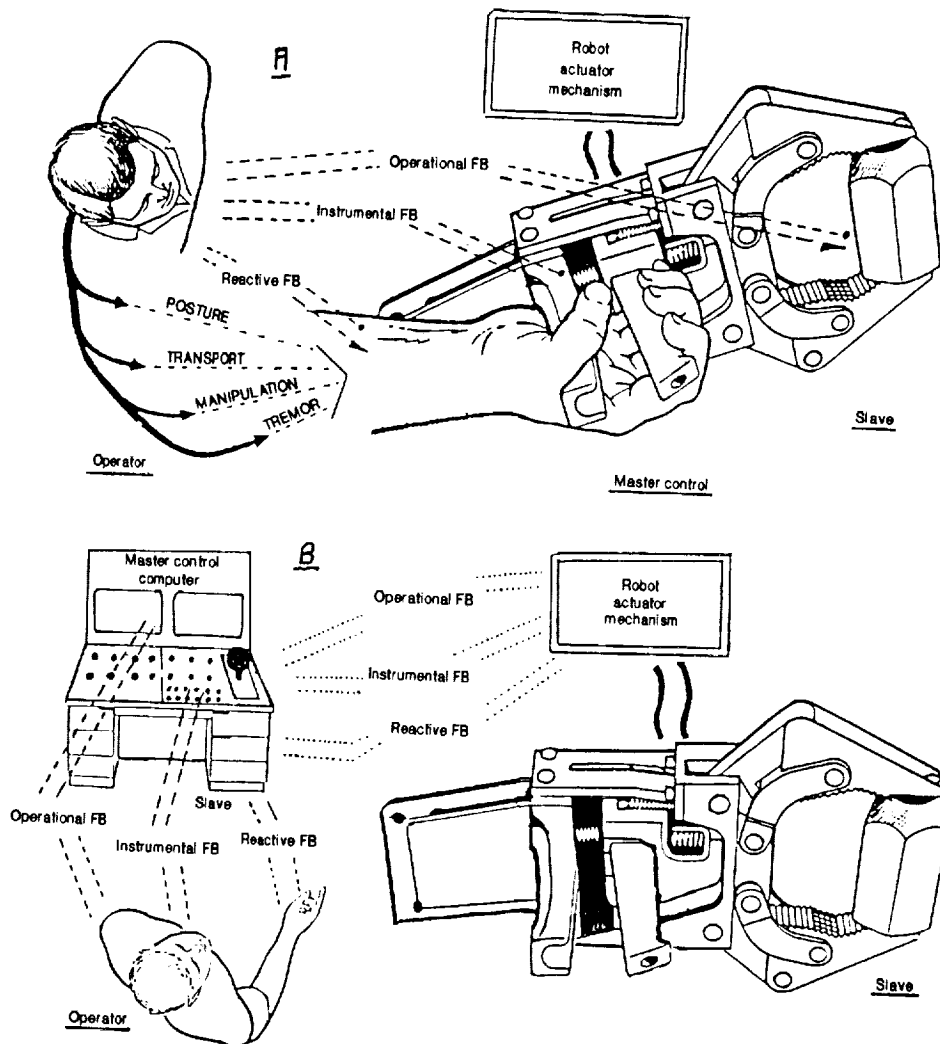


Figure 2. Sources of visual feedback in direct versus remote operation of a manual manipulator. Reactive feedback is from movement of limb or segment effector. Instrumental feedback is from effector-mediated movement of master-control component. Operational feedback is from action of slave component. A. Direct operator interaction with telerobot; B. Computer-mediated operator interaction with telerobot.

under the direction of Mosher [17,18]. The broad objective of the program was to develop mechanical devices which would serve as operator-controlled extensions of the body to expand the strength and endurance capabilities of human performance. The program dealt with four general types of CAMs: arm-claw manipulators, bipedal walking machines, quadrupedal walking machines, and ambulatory exoskeletons which enclosed the operator within body-like frames. These were true telerobotic devices, in that they each comprised master control, actuator, and slave subsystems which provided computer-mediated, servo-controlled spatial, temporal, and force feedback compliant with all modes and patterns of motorsensory feedback from the human operator's articulated arm, hand-wrist, leg, foot, and torso movements.

To measure system relationships between operator performance and machine feedback parameters (such as device position, servo gain, and force-feedback ratio), human-factors studies of the four types of CAMs were carried out. These studies were

guided by the general block diagram of an operator-computer-telerobot system illustrated in Figure 3. Figure 3 is based on the original design for a CAM system [18]. However, the figure has been adapted [11] to show a more detailed breakdown of the operator-workstation-telerobot interactions schematically illustrated in Figure 2B, including specifically the sources of reactive, instrumental, and operational sensory feedback provided to the operator from the master-control, actuator, and slave subsystems. The figure also has been modified to conform to current specifications [31,32,64] for the Space Station Flight Telerobotic Servicer (SSFTS), to be discussed further in a subsequent section.

Figure 3 emphasizes the complexity of sensory feedback relationships which must be built into telerobotic systems to provide fully compliant force and position feedback for effective telepresence. Force feedback to the operator is mediated by kinesthetic (also termed proprioceptive) mechanoreceptors in the muscles, tendons, and

joints, plus tactile receptors in the skin. Collectively, kinesthetic and tactile receptors provide muscle-tendon-joint sensibility, which encompasses pressure, movement position and dynamics (occurrence, locus, direction, velocity, and acceleration of movement), temperature, and pain [19, Chap. 14].

Mosher [17,18] established that four different dimensions of force feedback are needed to control body movement accurately, and should therefore be incorporated into a telerobot control system: (1) force of movement at different levels of exertion; (2) upper limit of force required; (3) prediction of force needed to execute movements of a given velocity and power; and (4) detection of relative displacement between movement and its sensory feedback. A series of system design and operational factors which influence the muscle-tendon-joint sensibility of the operator were identified, including force feedback ratios between operator and robot, drift on bias forces, friction thresholds, nonlinearity of force interactions, saturation factors, and force-signal integrity as influenced by system kinematics. As part of this human-factors system analysis, Mosher also demonstrated that force feedback related to the limits of exertion of

powered grips, lifts, and pulls must be built into telerobots as a safety precaution to prevent their destructive action, a finding with implications for present-day robotic systems [20].

Although theoretical and experimental demonstration of the fact that force feedback is needed to guide and control telerobotic machines was fully developed and confirmed by the work of Mosher [17,18], research conducted by the senior author of the present report established that effective workstation telepresence could not be achieved without also introducing spatial compliance in sensory feedback control of telerobotic action [11,21,22]. Such compliance occurs only when the position feedback system designated in Figure 3 embodies several spatiotemporal parameters of sensory feedback, namely position, direction, relative extent, range, velocity, acceleration, and form or pattern of telerobotic movement.

As described in the next section, the roles of spatiotemporal sensory feedback factors in human movement control were established in the course of an extensive program of experimental research on the effects of spatially and temporally perturbed sensory feedback on human behavior and performance [14, 23-29]. Findings from this research

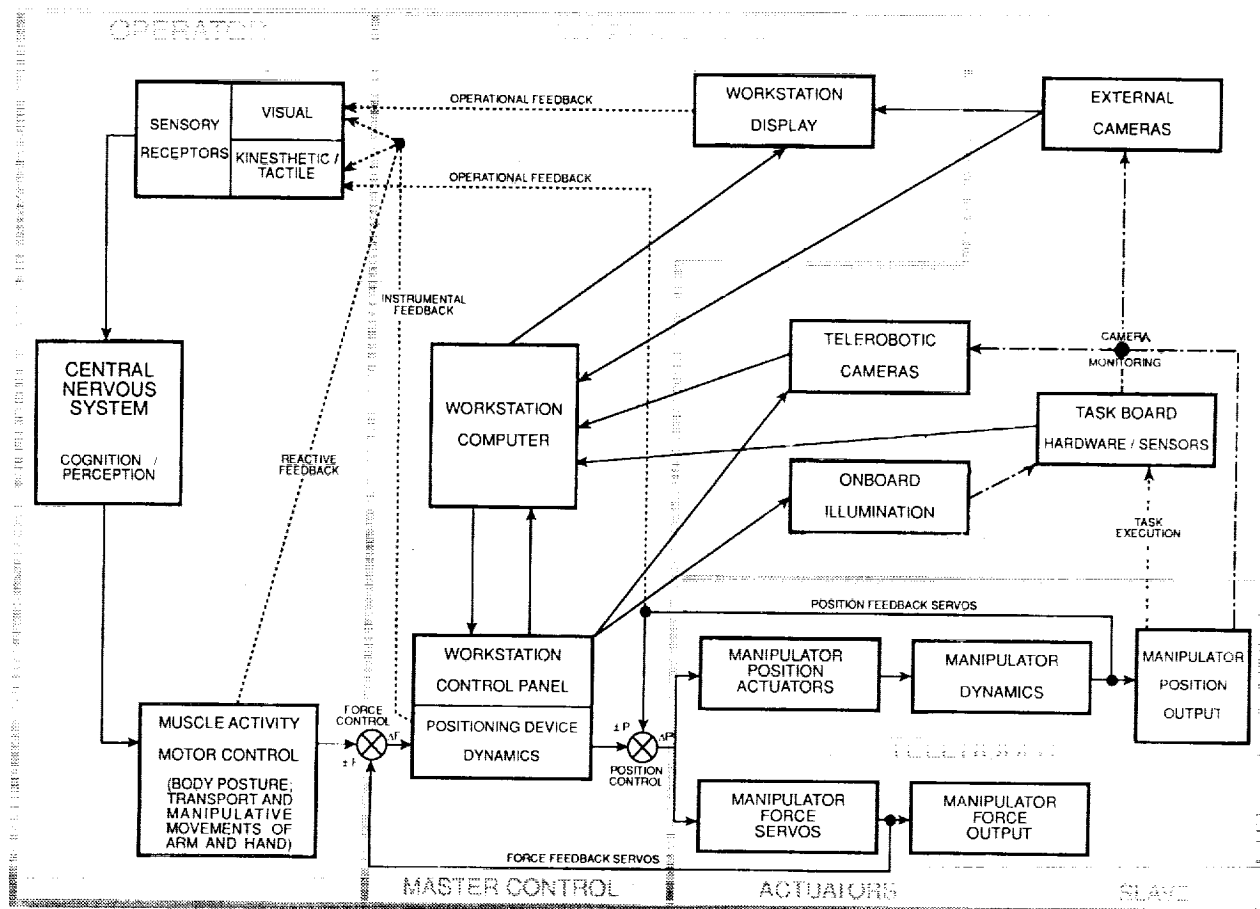


Figure 3. Block diagram of telerobot control system, indicating interactive roles of the operator, workstation, telerobot, and video cameras in system performance. Visual, position, and force feedback to the operator combines reactive, instrumental, and operational feedback generated by the master-control, actuator, and slave components of the system (Figure 2). The figure has been modified (from [11,18]) to include vision system components for a space telerobot [32].

demonstrate that all body movements are guided and controlled primarily by spatial feedback factors, with different movement systems mediated by different properties and dimensions of spatial feedback control. In general, tactile-kinesthetic mechanisms (for velocity, acceleration, and position control) are integrated with the visual and vestibular mechanisms (for control of position, direction, range, extent, and pattern of movement in space) in mediating the overall organization, predictive guidance, and integration of every movement pattern of the body.

Several characteristics of Mosher's original CAMs point up the importance of full spatial compliance for effective telepresence. For example, one problem that emerged in the design of the bipedal walking machines was inability of the operator to determine whether the machine was going down an incline versus falling backwards (or going up an incline versus falling forwards). To resolve this problem, Smith [21] demonstrated, first, that the operator's normal posture had to be maintained with respect to leg motion, and second, that the operator had to be able to sense any displacement of either leg of the machine with respect to the position of the machine cab. It was concluded that these cab-leg displacements had to be sensed by the operator via active force and position feedback. After appropriate torso-leg/cab-leg servo feedback mechanisms were incorporated into the design of the walking machine, it was found that even a novice operator could effectively control the dynamic balance of the machine.

A second example of the importance of spatial factors in telepresence emerged with research on manipulator CAMs. Tests showed that the operator of a manipulator experienced extension of his/her dynamic body image as long as just the manipulator was moved, but that this sensation was lost when the manipulator claw was moved. This loss of telepresence was related to the fact that the grasp actions of the claw were not spatially compliant with the operator's hand movements, although the force compliances were very adequate.

The two examples cited above demonstrate that body image is defined in large part by the spatial organization of body movement, and that the skill, precision, and safety of telerobotic operation are enhanced when the human operator perceives robot movements as an extension of his/her own movements. The general conclusion is that telerobotic design must incorporate compliances of both spatial and force factors between operator movements and machine movements before effective workstation telepresence can be established.

Although this conclusion is based on CAM research dating back two to three decades [17,18,21,22], we are not aware of more recent evidence which contradicts the insights it provides into the human factors of workstation telepresence, or that superior approaches to telerobotic design and control have been devised. Indeed, a recognized expert in the field recently referred to Mosher's machines as still among the most sophisticated telerobots yet developed [30].

EFFECTS OF PERTURBED SENSORY FEEDBACK ON INTERACTIVE PERFORMANCE

The remainder of this report summarizes

scientific evidence from perturbed sensory feedback research which indicates why spatially compliant feedback is critical to workstation telepresence, and explores the implications of this evidence for optimizing the human-factors design of interactive, telerobotic systems. Scientific interest in the phenomenon of perturbed sensory feedback dates back over a century to the early work of Helmholtz [33], who studied the effects of and adjustment to spatial displacements in visual feedback. Since then, the effects on human performance of both spatial perturbations and temporal delays in visual and auditory feedback have been the subject of numerous investigations, whose findings are summarized in a series of reviews published over the past three decades [14, 23-29,34].

In this report, the conceptual approach adopted to interpreting the performance effects of perturbations in sensory feedback is grounded in behavioral cybernetic theory. The basic postulate of this theory is that behavior is a closed-loop, self-regulated process mediated by motor control of sensory feedback [12,14,23-29]. From a behavioral cybernetic perspective, sensation and perception are feedback integrated with the motor system through motor coordinate feedback control of receptor processes and environmental stimuli. During task performance, the individual uses movement-based mechanisms to control spatial, temporal, or other types of perturbations in sensory feedback which may arise as a result of the human-factors characteristics of task design.

Since Helmholtz first posed the question, an important issue in psychology has been whether the spatial organization of behavior is innate or learned through experience. Although experiential learning appears to definitely contribute to the spatial guidance of behavior, experimental findings indicate that complete adaptation to perturbations in sensory feedback rarely occurs [14,23-29,34]. Instead, evidence indicates that performance and learning remain suboptimal in the face of persistent exposure to a perturbation condition. This suggests that the nature and degree of learning and performance proficiency achieved for a particular task depend upon the nature and degree of spatiotemporal compliance between sensory input and the motor feedback mechanisms controlling that input during task execution.

Figure 4 provides a diagrammatic illustration of the concept that workstation telepresence is critically dependent upon spatial compliance between sensory feedback and its motor control mechanisms, using the same master control-slave telerobot model as in Figure 1. In Figure 4, however, visual feedback has been spatially perturbed by reversing the lateral motion relationships between arm-controlled movement of the control component and derivative movement of the slave component. Consequently, the operator experiences a perturbation in the normal manner in which visual feedback from the telerobot manipulator is controlled by arm movement, telepresence is compromised, and performance suffers.

In general, four major classes of perturbations in sensory feedback may be identified, namely: (1) spatial transformations and/or displacements; (2) temporal delays; (3) changes in energy properties; and (4) modality conflicts. For example, control of visual feedback from a video-

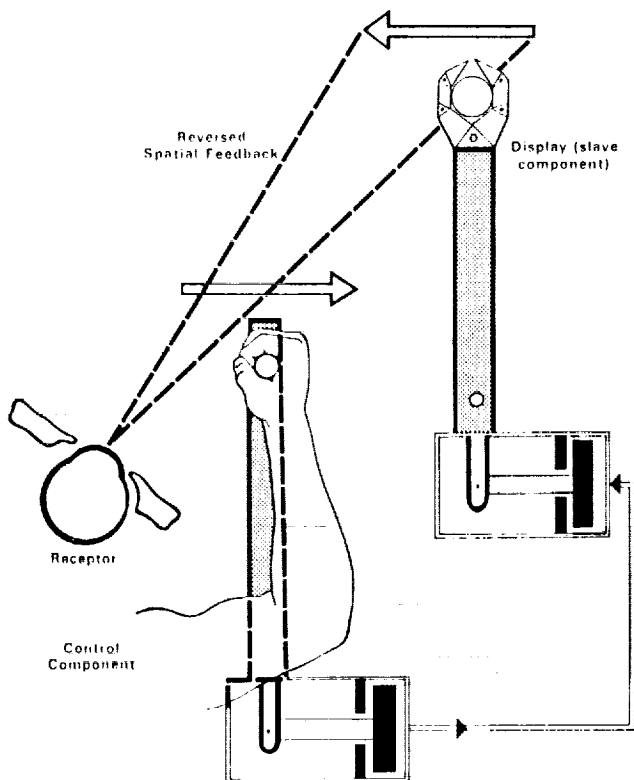


Figure 4. Spatial perturbation (reversed visual feedback) in visual-manual operation of a telerobot manipulator. Spatial compliance between movements of telerobot slave components, and control movements of the operator, represents one of the key human factors of workstation telepresence.

displayed image during remote telerobotic operation may be perturbed in each of these ways by: (1) inversion, reversal, angular displacement, magnification, or miniaturization of the displayed image; (2) feedback delay of the real-time display; (3) modulation of display quality due to glare, brightness, reflectance, contrast, and/or frequency shift effects; or (4) auditory and/or kinesthetic interference with visual feedback control. In extraterrestrial environments, microgravity represents a fifth class of sensory feedback perturbation which may exacerbate the effects of other types of perturbations [2,35-37].

Figure 5 expands upon Figure 4 with a schematic summary of the major sets of factors which potentially influence visual-manual task performance and workstation telepresence during operator interaction with a space telerobot such as the SSFTS. The diagram indicates that interaction of the operator (to the right) with the telerobotic system (to the left) across the operator-system interface is influenced by one or more of 14 possible perturbed sensory feedback factors specified in the figure and cited above. The operator-system interface specified in Figure 5 assumes the feedback relationships depicted in Figures 2 and 3, namely 3 sources of feedback (reactive, instrumental, operational) from the 3 telerobotic subsystems (master-control, actuator, slave).

Figure 5 also assumes that visual-manual performance is based upon use of the motor system (19 principle motor control factors specified) to feedback control the visual system (11 principle visual perception factors specified), involving 5 distinct modes of sensory feedback control [14,23-29]. This control process potentially may be influenced by a broad range of space telerobotic system design factors (18 principle design considerations specified), some of which may give rise to the perturbation conditions indicated in the figure. The system design, visual perception, and movement control factors specified in Figure 5 are compiled from basic human-factors considerations regarding telerobotic operation [11], plus recent analyses by various scientific specialists in space telerobotic research [32,38-41].

Some appreciation of the scientific challenge confronting systematic investigation of the human factors of workstation telepresence may be gained by considering that there are over 2.3 million possible combinations of performance, design, and feedback factors ($14 \times 3 \times 3 \times 19 \times 11 \times 5 \times 18$) which potentially can influence operational variability in visual-manual control of a space telerobot, based on specifications in Figure 5 and summarized above. That it probably is not feasible to completely evaluate even a reasonable subset of such possible combinations raises the question of research priorities and emphasis in human-factors analysis of performance variability in telerobotic operation. The hypothesis adopted in this report is that spatiotemporal perturbations in sensory feedback constitute a major source of variability in human performance with automated and telerobotic systems, and that this issue therefore merits attention by human-factors research aimed at optimizing workstation telepresence. Evidence in support of this hypothesis is summarized in the next section.

Experimental Observations On Perturbed Sensory Feedback Effects

Over the past three decades, the most extensive program of experimental research on perturbed sensory feedback phenomena has been conducted by K.U. Smith and colleagues [14,23-29,34]. This work has focused primarily upon delineating the effects of spatial and temporal perturbations in sensory feedback on learning and performance. For this purpose, computer- and video-based techniques are used to introduce controlled spatial transformations or displacements, and/or temporal delays, in sensory feedback (usually visual or auditory) provided to subjects of their own task performance. A wide range of different cognitive and motor behavioral skills have been examined in this manner, including machine performance, tool using, musical performance, reading, writing and drawing, tracking and steering, speech, memory, eyemovement control, visual perception, motor coordination, postural control, behavioral-physiological integration, and social interaction [28,29,42,43].

With its use of computer and video-display techniques, this research essentially represents the application of interactive, human-computer laboratory methodology to the study of how perturbations and distortions in sensory feedback

influence learning, performance, and workstation telepresence. However, rather than arising as an incidental and unwelcome concomitant of human-factors defects in interface design, such perturbations are introduced deliberately by the computer under controlled laboratory conditions, so that effects can be assessed in an objective and quantitative fashion. The research approach therefore provides a methodological paradigm for systematic study of the contribution of sensory feedback perturbations to variability in human interaction with automated and telerobotic systems, in relation to human-factors design features of the interface [11,14].

The general conclusion from the extensive body of research conducted using this approach is that the performance and learning of every behavioral task so far examined is degraded by perturbations in sensory feedback [14,28,29]. Tables 1 and 2 provide representative data on the nature and extent of these effects, for spatial transformations and temporal delays in sensory feedback respectively. All data are derived from controlled laboratory study of subject interaction with computer-or video-based systems. In both tables, performance changes for a series of tasks under specified perturbation conditions are summarized, along with information regarding experimental conditions and reference citations (first column).

Under spatially perturbed visual feedback conditions, results for various measures of seven distinct types of tasks are given in Table 1 (third column), namely writing, drawing, reading, assembly, panel control, tool using, and tracking tasks. The spatial perturbation conditions examined (second column) encompass inversion, reversal, combined inversion and reversal, angular displacement, and

size reduction (miniaturization) of visual feedback. The measures used to assess performance (fourth column) vary for different tasks, but generally fall into the categories of movement characteristics (contact, travel, grasp, or assembly times), or performance accuracy. Results (last column) are expressed as percent change in performance, from the control to the spatial perturbation condition, at the start and at the end of a training period (fifth column) which typically involved one or more trial sessions per day over a series of days. An asterisk is used in the last column to denote the statistical significance of the performance change observed.

Results for the feedback delay studies in Table 2 are summarized in much the same manner. These studies examined writing, drawing, tracking (manual, eye, and head movements), speech, memory, and interactive social tracking tasks (second column), with performance again assessed using either movement characteristics or accuracy measures (third column). Results (last three columns) are presented as the change in performance, for delay in either visual or auditory feedback, at delay intervals of 0.2 seconds, 0.4 seconds, and the

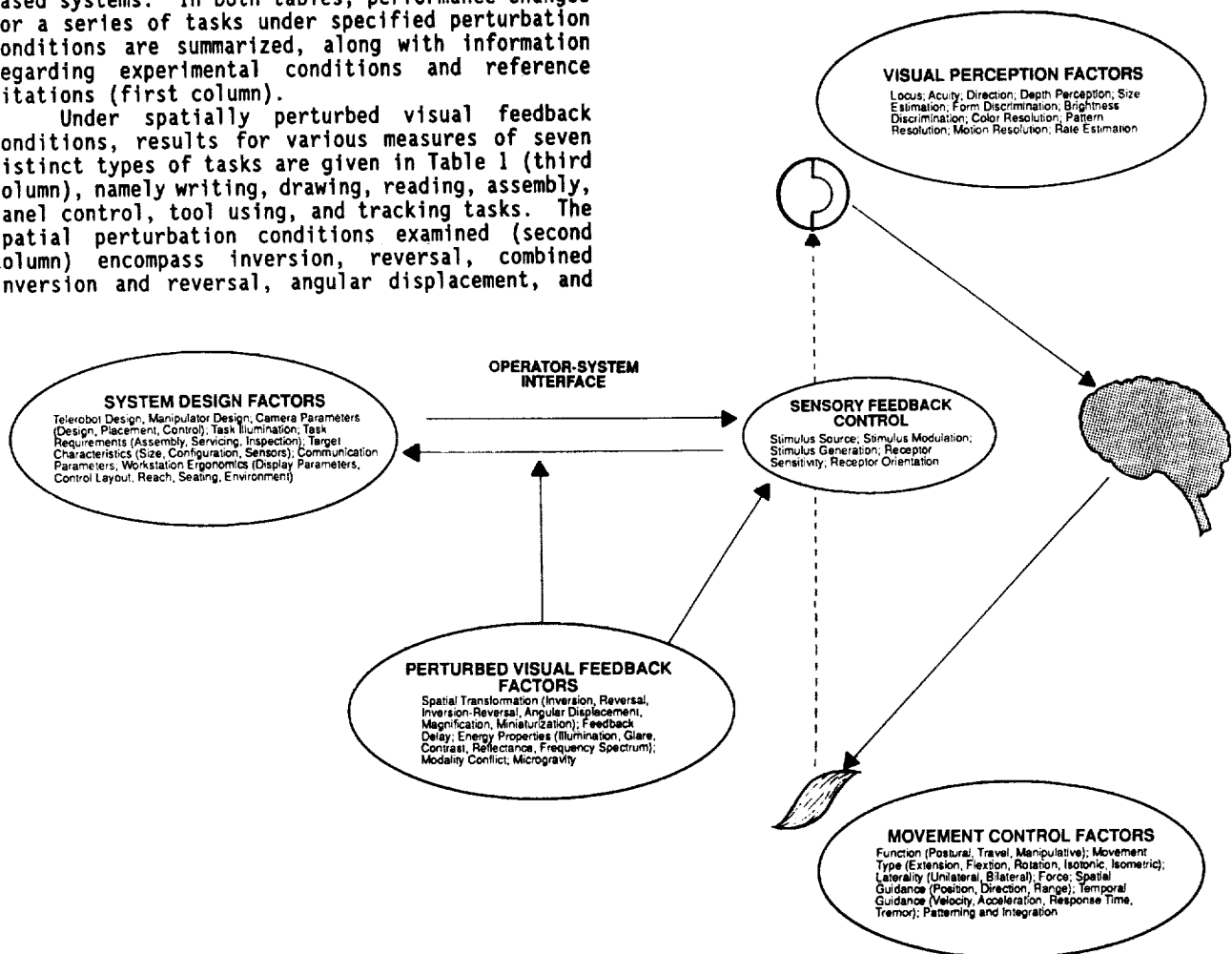


Figure 5. Human factors which may influence workstation telepresence in space telerobotic operation. Operator performance involves motor control (movement and sensory feedback control factors) of visual feedback (visual perception factors), which is influenced by both system design and perturbed visual feedback factors.

maximum delay interval examined in the study, relative to performance under the no delay condition. Performance change values for the delay conditions are expressed as multiples of the zero-delay levels. In all of the studies cited in Table 2, analysis of variance was used to assess the overall contribution of the delay condition to the performance variability observed. In every case, the overall contribution was found to be statistically significant, but tests of significance at individual delay levels were not performed.

Results summarized in Tables 1 and 2, plus findings from an extensive body of related research, support the following conclusions regarding the effects of spatial and temporal perturbations in sensory feedback on interactive performance [14,23-29].

1. Performance and learning of every behavioral task so far examined are degraded by such perturbations. Consistent patterns and features of behavioral disturbance appear from study to study. Oscillatory instability in movement control becomes more pronounced, accompanied by increased variability and extremes in movement velocities and accelerations. Accuracy of movement guidance and tracking declines. Perception is disturbed and, in some cases, may disappear entirely; there is a concomitant deterioration in learning. Subjects report feeling confused, uncertain, and/or uncomfortable about their behavior. Skilled performers are particularly sensitive to these effects.

Table 1. Changes in Interactive Performance and Learning Under Spatially Perturbed Visual Feedback

Reference-Subjects ¹	Perturbation Condition ²	Task	Measure	Days of Training (Trials) ³	Performance Change (%) ⁴	
[44] - 12	I	.Hand-writing	.Contact	0 (1)	+ 676 %	*
"	"	"	Time	20 (20)	+ 153	*
"	"	"	.Travel	0 (1)	+ 410	*
"	"	"	Time	20 (20)	+ 8	
"	"	.Drawing	.Contact	0 (1)	+ 493	*
"	"	Triangles	Time	20 (20)	+ 71	*
"	"	"	.Travel	0 (1)	+ 583	*
"	"	"	Time	20 (20)	+ 33	
"	"	.Reading	.Amount	0 (1)	- 81	*
"	"	Words	Read	5 (5)	- 12	*
[45] - 4	I	.Reading	.Time x	0 (1)	+ 253	*
"	"	"	Error	5 (5)	+ 21	
"	R	"	Score	0 (1)	+ 210	*
"	"	"	"	5 (5)	+ 6	
[24] - 10 (p. 163)	I-R	.Assembly	.Grasp	0 (1)	+ 5	*
"	"	"	Duration	4 (4)	+ 4	*
"	"	"	.Loaded Tra-	0 (1)	+ 24	*
"	"	"	vel Duration	4 (4)	+ 6	
"	"	"	.Assembly	0 (1)	+ 92	*
"	"	"	Duration	4 (4)	+ 60	*
"	"	"	.Nonloaded	0 (1)	+ 27	*
"	"	"	Travel	4 (4)	+ 8	
"	"	"	Duration			
[24] - 24 (p. 171)	I	.Hand-writing	.Contact	2 (4)	+ 286	*
"	R	"	Time	"	+ 154	*
"	I-R	"	"	"	+ 250	*
"	I	"	.Travel	"	+ 240	*
"	R	"	Time	"	+ 160	*
"	I-R	"	"	"	+ 200	*
"	I	.Drawing	.Contact	"	+ 171	*
"	R	Triangles	Time	"	+ 80	*
"	I-R	"	"	"	+ 105	*
"	I	"	.Travel	"	+ 139	*
"	R	"	Time	"	+ 72	*
"	I-R	"	"	"	+ 94	*
[24] - 24 (p. 172)	I	.Maze	.Accuracy	0 (1)	- 72	*
"	R	Tracing	"	"	- 51	*
"	I-R	"	"	"	- 39	*
"	I	"	"	3 (9)	- 37	*
"	R	"	"	"	- 15	*
"	I-R	"	"	"	- 25	*

Table 1. (continued)

Reference-Subjects ¹	Perturbation Condition ²	Task	Measure	Days of Training (Trials) ³	Performance Change (%) ⁴	
[24] - 18 (p. 218)	.Size Reduction (to 1/3 size)	.Panel Control	.Contact Time	0 (1)	+ 108	*
"	"	"	.Travel Time	5 (40)	+ 104	*
"	"	"	"	0 (1)	+ 232	*
"	"	"	"	5 (40)	+ 267	*
[24] - 24 (p. 239)	I	Tool Using:				
"	"	.Dial Setting	.Manipulation Time	0 (1)	+ 273	*
"	"	.Turning	"	7 (21)	+ 117	*
"	"	"	"	0 (1)	+ 191	*
"	"	"	"	7 (21)	+ 78	*
"	"	.Pushing	"	0 (1)	+ 200	*
"	"	"	"	7 (21)	+ 100	*
"	"	.Pressing	"	0 (1)	+ 250	*
"	"	"	"	7 (21)	+ 117	*
"	"	.Dial Setting	.Travel Time	0 (1)	+ 257	*
"	"	.Turning	"	7 (21)	+ 29	*
"	"	"	"	0 (1)	+ 209	*
"	"	"	"	7 (21)	+ 40	*
"	"	.Pushing	"	0 (1)	+ 218	*
"	"	"	"	7 (21)	+ 36	*
"	"	.Pressing	"	0 (1)	+ 230	*
"	"	"	"	7 (21)	+ 40	*
[46] - 24	AD:					
"	20 degrees	.Maze Tracing	.Errors	0 (1)	+ 6	
"	40 degrees	"	"	"	+ 5	
"	60 degrees	"	"	"	+ 23	*
"	10 degrees	"	"	10 (10)	- 2	
"	20 degrees	"	"	"	- 9	
"	30 degrees	"	"	"	+ 2	
"	40 degrees	"	"	"	+ 7	
"	50 degrees	"	"	"	+ 63	*
"	60 degrees	"	"	"	+ 148	*
"	70 degrees	"	"	"	+ 287	*

*Change from nonperturbed visual feedback performance level is statistically significant (p<.05).

¹Reference in brackets, followed by number of subjects.

²I = Inversion; R = Reversal; I-R = Inversion-Reversal; AD = Angular Displacement (in degrees).

³Number of trials in parentheses.

⁴Performance change, in percent, calculated as:

$[(\text{perturbed viewing level} - \text{nonperturbed viewing level}) \times 100] / (\text{nonperturbed viewing level})$

2. For untrained subjects, spatial perturbations in visual feedback have profound effects on task performance. In Table 1 for example, there are statistically significant performance decrements for 24 of 27 no training cases (fifth column, trial 1, 0 days training), and in 20 of these cases the performance decrement exceeds 50 percent.

3. After training, subjects typically exhibit improved performance under spatially perturbed visual feedback conditions. In Table 1 for example, there are 27 instances in which pre- and post-training performance levels can be compared, and performance improved in 25 of these cases. Nevertheless, with rare exceptions, under spatially perturbed visual feedback subjects do not perform at the same level as under nonperturbed conditions, even after a training regimen lasting as long as 20 days. In Table 1 for example, statistically significant performance decrements persisted for 33

of 43 cases in which training was provided for 2 days or longer. A similar pattern has been observed in experiments where subjects were exposed continuously to spatially perturbed visual feedback for periods of time lasting days or weeks [24,34].

4. The training findings summarized in Point 3 suggest that human learning is refractory to complete adaptation to spatial perturbations in visual feedback. Neurobiological corroboration of this conclusion is provided by recent research [52,53] on motor learning in the primate vestibulo-ocular reflex (VOR). Under continuous exposure to size distortion (magnifying or miniaturizing spectacles), both the reflex gain and activity of brain stem neurons mediating the reflex adjust accordingly. However, the gain error increases from about zero, with no distortion, to 10-20 percent under the distortion condition. This lack of complete adaptation to size perturbation may explain

Table 2. Changes in Interactive Performance Under Feedback Delay¹

Reference-Subjects ²	Task	Measure	Performance Change (x1) at Specified Delay ³		
			0.2 sec	0.4 sec	Max (sec) ⁴
[23] - 2	.Writing Letters	.Contact Time	-	-	+ 2.4x (.52)
"	.Drawing	"	-	-	+ 1.1x (.52)
"	.Star Tracing	"	-	-	+ 4.6x (.52)
"	.Maze Tracing	"	-	-	+ 5.0x (.52)
[47] - 8	.Head Movement Tracking of Visual Target	.Tracking Error	+ 1.3x	+ 1.6x	+ 2.3x (0.8)
[48] - 8	[auditory delay interval ⁵ : .Speech	.Speech Errors	[0.1 sec + 4.1x	[0.2 sec + 11.1x] + 14 x (0.3)
[49] - 12	Tracking of Visual Target: .Eye Movement .Head Movement .Head-Eye Movement	.Tracking Error " "	+ 1.2x + 1.2x 0 x	+ 1.2x + 1.2x + 1.2x	+ 2.0x (1.6) + 5.0x (1.6) + 1.9x (1.6)
[50] - 8	.Memory of Visual Image	.Recall Error	+ 1.5x	+ 1.9x	+ 3.3x (0.8)
[51] - 2	.Visual-Manual Tracking -Individual: -Social :	.Tracking Error " "	+ 1.1x + 1.5x	+ 1.5x + 1.8x	+ 2.6x (1.5) + 3.0x (1.5)

¹All studies examined visual feedback delays, except for Abbs and Smith [48], who examined auditory feedback delay.

²Reference in brackets, followed by number of subjects.

³Performance change, in multiples of one (indicated by small x), observed at delay intervals of 0.2 sec, 0.4 sec, and maximum delay interval examined⁴. Performance change is calculated as:

$$\frac{(\text{Delayed Performance Level})}{(\text{No Delay Performance Level})}$$

⁴Performance change, in multiples of one⁵, at maximum feedback delay interval examined in study. The maximum delay interval examined, in seconds, is indicated in parentheses.

⁵Delay intervals of 0.1 sec, 0.2 sec, and 0.3 sec examined in this study.

the finding cited in Table 1 that performance by human subjects in an interactive panel control task remained significantly impaired after 5 days of training with use of miniaturizing spectacles that provided a two-thirds size reduction [24, p. 218].

5. Three experiments described in Table 1 [24, pp. 171-172; 45] directly compared the effects of inversion, reversal, and combined inversion-reversal of visual feedback. The results indicate that inversion has the most adverse impact on performance, followed in order by combined inversion-reversal, and reversal alone. Other research also supports this conclusion [25].

6. Under conditions of angular displacement of visual feedback, as indicated in the last study cited in Table 1 [46], performance remains relatively unaffected until a displacement angle of 50 degrees is imposed. This finding has been interpreted as providing evidence for a breakdown angle of spatial displacement, beyond which performance becomes progressively more difficult. Typically, the breakdown angle falls in the range of 40 to 50 degrees displacement. Results in Table 1 indicate that even after 10 days of training, performance under displacement conditions exceeding

the breakdown angle remains significantly impaired.

7. Relative to direct viewing conditions, performance on an assembly task is impaired under television viewing of the assembly operation, even when no deliberate spatial distortions are introduced [24, pp. 161-163]. This may be attributed to inherent spatial distortions in visual feedback introduced by the video camera and display system.

8. Performance under spatially perturbed visual feedback varies as a function of both age and gender [45,54].

9. Temporal perturbations (feedback delays) in sensory feedback also result in consistent decrements in performance, as illustrated by the findings cited in Table 2. Performance decrements at a delay interval of 0.2 sec occur for eight of nine tasks listed in the table. At delay intervals of 0.3 sec and greater, all 13 tasks listed in the table manifest performance decrements. For speech, a fourfold increase in errors is observed at an auditory feedback delay of 0.1 sec [48].

10. Training effect data are not included in Table 2 because the studies that have been done (on both eyemovement tracking and memory) indicate little or no performance improvement with learning under feedback delay conditions [47,55].

11. When visual feedback is both temporally delayed and spatially reversed in either an eye- or a head-movement tracking task, the delay exacerbates the decrement in tracking performance produced by the reversal condition [47,55].

12. Social tracking involves the mutual exchange and control of sensory feedback among two or more individuals during group activity [13,28,56]. Salient findings regarding social tracking are that: (a) relative to visual-manual social tracking, accuracy is higher for tactile or auditory social tracking [57]; (b) social tracking accuracy is comparable to individual tracking accuracy except under feedback delay conditions, when the latter is superior to the former at all delay levels [51]; (c) learning of social tracking tasks is limited, highly variable and inconsistent, and unstable [58,59]; and (d) the preponderance of performance variability in social tracking is attributable, not to a learning effect, but to human-factors characteristics of task design [60].

Space Telerobotic Telepresence Operational Implications of Perturbations in Sensory Feedback

A major assumption of this report is that the findings and conclusions summarized in the preceding section have direct relevance to understanding possible effects of perturbed sensory feedback on interactive performance in extraterrestrial environments. For example, many of the tasks listed in Tables 1 and 2 (reading, tracking, assembly, panel control, tool using, speech, memory, social tracking) are employed during interactive human performance with space telerobotic systems. Smith and colleagues [61] have addressed this question, and conclude that perturbed sensory feedback effects could have a potentially decisive influence on the performance of useful work with man-in-the-loop space telerobotics. Some experimental evidence from earth-based, human-factors research on telerobotic systems lends support to this conclusion, as summarized below.

Establishment of high fidelity workstation telepresence for space telerobotic operators will require that inappropriate or hazardous sensory feedback from the space environment be eliminated (i.e., direct sunlight, glare, cold, lack of air), whereas visual, tactile, kinesthetic, and auditory feedback essential to manipulative performance is provided which conforms to the control capabilities of the operator. During performance of a remote manipulation task with a telerobot in space, it may be possible to view the remote scene directly through a window. For most tasks, however, a direct view either will not be available, or will not provide the appropriate visual cues necessary for teleoperation (due to distance and/or interposition of other objects). For this reason, external cameras will provide the primary source of visual feedback about manipulator position, orientation, and rate of movement [62].

Various studies of viewing system requirements for space telerobotic systems indicate that perturbations in visual feedback may represent a pervasive feature of teleoperation. A number of authors agree [38-41] that visual guidance of space station telerobotic tasks will be influenced by extreme illumination, contrast, glare, and reflectance conditions known to exist in space. In addition, recent research by R. Smith and colleagues [32,39,62,63] has addressed the question of how spatial perturbations in visual feedback, produced by camera-induced transformation of the manipulator reference plane relative to that of the operator, could degrade task performance of the telerobot operator and thereby risk damage or loss of the manipulator or payload. In particular, spatial perturbations of visual feedback to the operator from a space telerobot can be predicted as a result of: (1) variable orientations of surveillance cameras on the station gridwork and modules, and on the telerobot; (2) lack of a fixed ground reference; (3) abnormal or missing depth cues; and (4) extreme viewing conditions, as noted above.

Decremental effects of spatial transformations in visual feedback on remote operation of a telerobot have been confirmed in a recent laboratory study by Stuart and Smith [63], who show that telerobot manipulation times are: (1) significantly slower for video-display viewing of the worksite, relative to direct viewing; and (2) slowed most by inversion of visual feedback, with reversal and inversion-reversal conditions having less of an effect. In particular, these researchers found that performance completion times in a manipulator positioning task were increased by the following amounts, relative to direct viewing of the task: (1) display viewing, 2.0-fold increase (no other spatial perturbation); (2) inverted-reversed viewing, 8.5-fold increase; (3) reversed viewing, 10.2-fold increase; and (4) inverted viewing, 16.1-fold increase. As indicated in Table 1, these findings recapitulate the earlier observations of K.U. Smith and colleagues [24], in which the same techniques of video camera displacement and rotation were used to spatially perturb visual feedback of the task provided to subjects.

Also recapitulating earlier observations [23] are results from recent research on operation of a laboratory version of a telerobot servicer [15], which demonstrate that delays in visual feedback significantly increase manipulation performance times. The earlier research documented the detrimental effects on tracking performance of delay intervals ranging from one to three seconds (in the same range as the round-trip transmission delay for a signal from an earth-bound operator to an orbiting or moon-based telerobot), and was among the first to point out that effective guidance of a remote telerobot would be seriously compromised by delays in visual feedback [23, pp. 94-96].

A further important consideration in establishing telerobot workstation telepresence is that of sensory feedback modality and its control. For example, in an experimental study of visual and tactile social tracking [25], it was shown that an observer can track an irregularly moving object more accurately by touching it (tactile-kinesthetic feedback) than by watching it (visual feedback). The difference is attributable to the slower feedback relationships of the visual system as

compared with those of the tactile-kinesthetic system. There also is the question of modality compatibility between sensory feedback and sensory feedback control. For example, feedback of force information from a telerobot force transducer to a hand controller, rather than as visual or auditory feedback, is compatible with human kinesthetic senses that are directly interpretable.

An appreciation of the potential for spatiotemporal perturbations in sensory feedback during SSFTS operation may be gained from a consideration of current system requirement specifications [31], as embodied in the general system diagram in Figure 3. Vision system specifications call for at least four telerobot-mounted video cameras, including one on the manipulator wrist, with separate positioning, orientation, zoom, focus, and aperture control capabilities indicated for each camera. Variable control of attitude and imaging parameters for both the telerobot-mounted and external cameras, coupled with possibilities for variability in task board and telerobot manipulator geometry, introduce a virtually unlimited potential for reversal, inversion, angular displacement, magnification, and/or miniaturization (Figure 5) of the display image presented as visual feedback to the human operator.

SSFTS manipulator specifications call for kinesthetic feedback of force, position, and rate information from sensors at each joint [31,64]. For purposes of task execution, the specifications also call for an orientation accuracy of less than 1.0 inch in manipulator tool plate center position, repeatable to an accuracy of less than 0.005 inch. However, findings summarized in Tables 1 and 2, plus observations from more recent perturbed sensory feedback research on telerobots [15,63], suggest that such accuracy may be compromised by the occurrence of any type of spatiotemporal perturbation in visual feedback. Under earth laboratory conditions, such perturbations cause errors in movement trajectory guidance plus increased oscillatory instability in static positioning control [23-29,64]. In addition, experience from earlier work on Mosher's CAM systems [11], summarized previously, suggests that it may be necessary to supplement kinesthetic and visual feedback with tactile feedback from manipulator end effectors in order to achieve a high degree of reproducible accuracy in control of manipulator positioning.

OPTIMIZING WORKSTATION TELEPRESENCE - A SOCIAL CYBERNETIC PERSPECTIVE

The analysis in the preceding sections suggests that effective workstation telepresence depends on provision of compliant sensory feedback across different modalities which can be readily controlled by the operator. Because they can compromise such compliance, perturbations in sensory feedback may significantly impair the operational effectiveness of space telerobotic systems, in relation to visual-manual control of manipulator functions. This raises the question as to what strategies might prove useful in reducing possible adverse effects of sensory feedback perturbations on human performance in space, in order to achieve high

fidelity workstation telepresence. Training is one obvious choice. However, evidence cited in Tables 1 and 2 suggests that even extended training will not completely overcome these effects. It may therefore prove desirable, or even necessary, to develop techniques which enable the interactive computer to detect, and then correct, perturbations in sensory feedback before presentation of such feedback to the human operator.

The idea of enlisting the workstation computer as an intelligent co-participant in optimizing workstation telepresence is in line with proposals by various authors that the design of space telerobotic systems should evolve from primary reliance on operator control to reliance on both operator and autonomous, computer-mediated (robotic) control of task execution [1-3,65-67]. To provide a conceptual foundation for dealing with the human factors of workstation telepresence at various levels of interactive complexity, we have developed a social cybernetic model of human-computer interaction [12-14]. The model, shown in Figure 6A, assumes that behavioral cybernetic principles of human social interaction [28,56,58-60] also can be applied to an understanding of human-computer interaction.

The term social tracking used in Figure 6A refers to the feedback-controlled process by which an individual engaged in social behavior follows or tracks one or more social targets. During social tracking, the activities of one person in a social group effect behavioral-physiological changes in the other social partners, whose own activities in turn have behavioral-physiological feedback effects on the first. These effects arise as a consequence of control by each participant of sensory feedback generated by the other social tracking partners. During interpersonal social tracking for example, the movements of one individual generate sensory feedback that is controlled by tracking movements of the social partner, whose actions generate compliant sensory feedback for the first individual, who in turn tracks this social feedback with further movement, and so forth. The two social partners thus become dynamically yoked or interlocked behaviorally and physiologically, through mutual tracking and control of sensory feedback generated by each other's social behavior. Through such social tracking interlocks, participants in a social group begin to operate as an integrated system, with definite systems feedback parameters and control characteristics.

The premise of the model in Figure 6A is that the interactive computer can be considered as a machine analog of a human social partner, and can be imbued through adaptive programming with capabilities for tracking and controlling, across different modalities, sensory feedback generated both by its own activities as well as those of its human partner. Unfortunately, because of technological and design limitations in such capabilities, today's interactive computer system is a relatively limited and impoverished social tracking target for the human operator. Broadly speaking, the creation of effective workstation telepresence requires that such limitations be overcome.

A number of authors have suggested that the quality and nature of crew social interaction are an important determinant of operational effectiveness

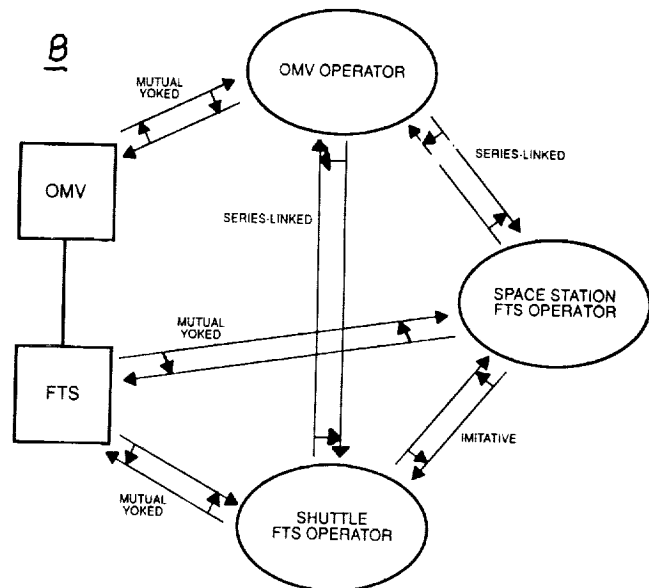
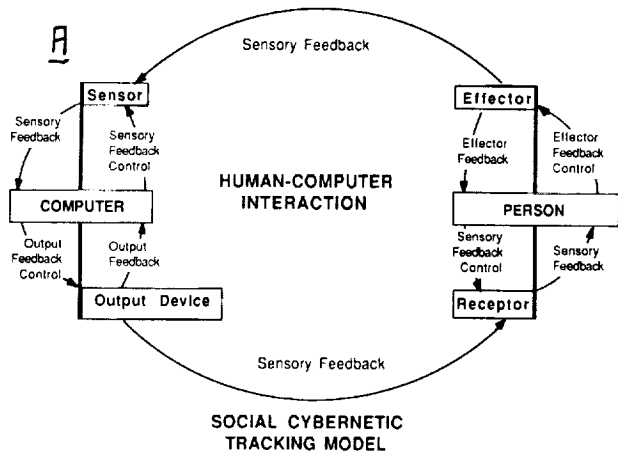


Figure 6. The social cybernetics of workstation telepresence. A. The social cybernetic model of human-computer interaction, which assumes mutual social tracking by operator and machine of sensory feedback generated by the other partner during interactive performance. B. Possible social cybernetic interactions during SSFTS operation. The diagram assumes that the SSFTS (which may be controlled by more than one operator) is conveyed to the task site by an Orbital Maneuvering Vehicle (OMV), controlled by a separate operator. The arrows symbolize possible sensory feedback exchange and control relationships between operator and machine participants in the control system. Also indicated are the most likely modes of social tracking for each relationship [13].

and safety in space [68]. Factoring possible human-computer interactions into the social tracking matrix further complicates the social cybernetics of flight crew performance. Figure 6B illustrates this point with a diagram of some of the interpersonal and human-computer social interactions which may be required for SSFTS operation. Current plans [1-3] call for the SSFTS to be conveyed to its task location by a transport device called the Orbital Maneuvering Vehicle (OMV). It is envisioned that the OMV and the SSFTS each will be controlled by a separate operator. In addition, current specifications [31] call for monitoring of telerobotic activities by multiple workstations (such as on the space station and shuttle), with the capability of handing control from one workstation to another. The various mutual social tracking interactions suggested by these plans are indicated in Figure 6B. The diagram also indicates the specific type of social tracking [13,56] which is most likely to be employed for the relationship specified.

The general implication of the diagrams in Figure 6 is that an analysis of the human factors of workstation telepresence requires consideration, not only of the social tracking fidelity for a particular operator-workstation-telerobot system, but also of the social tracking relationships between all of the players, human and computer, involved in system operation. That high fidelity social tracking requires effective control of sensory feedback from two sources---generated by self-activity and by activity of the social partner(s)---suggests two broad themes for human factors and engineering research aimed at improving workstation telepresence [12,13].

First, computer capabilities for detecting and adaptively controlling sensory feedback from its own sensors need to be enhanced. One useful outcome of such research could be automated, computer-mediated transformation of spatially perturbed images from cameras linked to the computer (see Figure 3). Secondly, computer capabilities for detecting and controlling sensory feedback from the human operator need to be enhanced. One useful outcome of such research could be improved techniques for automated detection of behavioral and physiological manifestations of operator decremental performance under spatiotemporally perturbed sensory feedback conditions, signalling need for computer-mediated correction of the perturbation. The human factors of workstation telepresence will benefit from the development of more robust strategies for automated control of sensory feedback, growing out of research on the social cybernetics of human-computer systems, which enable improved system management of spatiotemporal perturbations in sensory feedback.

SUMMARY

This report has presented a human-factors analysis of workstation telepresence which supports the following major conclusions:

1. Pioneering human-factors research on operational requirements for cybernetic anthropomorphic machines has established that spatial compliance between postural, transport, and manipulative movements of the operator and those of the CAM is essential to the creation of high fidelity workstation telepresence.

2. An extensive body of behavioral cybernetic research evidence indicates that spatial and temporal perturbations in visual and auditory feedback degrade learning and performance of every behavioral task so far examined. The findings have direct relevance to the human factors of human-computer interaction, in that the research itself made use of interactive computer- and video-based methods to deliberately introduce and evaluate the effects of such perturbations.

3. Although training improvements occur, this research has found no evidence to indicate that humans can adapt perfectly to spatial and/or temporal perturbations in sensory feedback which are not compliant with established motor feedback control mechanisms.

4. Because of noncompliant human-factors design features, sensory feedback perturbations arise routinely in the course of operational human interaction with telerobotic systems. Performance decrements even occur when video display viewing of a task is substituted for direct viewing.

5. A number of different modes and sources of sensory feedback perturbations can be identified which may potentially influence interactive human performance during space telerobot operation. Results from recent laboratory research using remote telerobot servicers show that manipulation tasks are adversely affected by both spatial perturbations and temporal delays, confirming in part the findings from earlier behavioral cybernetic research.

6. The human factors of workstation telepresence encompass the distinct social dynamic attributes of telerobotic systems, involving mutual sensory feedback exchange and control relationships among multiple human operators, computers, and telerobots. A social cybernetic model of human-computer interaction is described which uses social tracking concepts to characterize the sensory feedback control relationships among human and machine participants in complex, interactive systems. Current plans suggest that such social relationships will be an integral part of space station teleoperations, where station-, shuttle-, and ground-based systems may all be involved in mediating telerobotic tasks. One projection from the social cybernetic model is that a research emphasis on improving the capabilities of the interactive computer for controlling sensory feedback, from its own performance as well as from that of the human partner, will benefit the development of workstation telepresence.

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